Thesis

AUTOMATIC CONTROL OF THE TERMINAL VOLTAGE OF A 12.5-KVA ALTERNATOR

OG

by

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AN ESSAY

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INTRODUCTION

The increasing need for an automatic voltage regulator to meet the exacting requirements of industrial and laboratory service has led to innumerable attempts to produce a device which will keep the terminal voltage of an alternator constant as the load is varied. If an alternator has its field current adjusted so as to supply rated voltage at no-load and rated frequency, the terminal voltage decreases as resistive or inductive loads are applied and increases as capacitive loads are applied to the machine. In order to prevent this the generated voltage of the machine must be controlled by controlling the field current to compensate for the variable impedance drop and the variable demagnetizing effects.

The first successful attempts at automatic control of the terminal voltage of alternators were made with various types of vibrating contact devices such as the Tirrill regulator.[14] In addition to their being relatively slow in response to the changing loads, the deterioration by use of the moving parts and the necessary frequent adjustment made them undesirable. It was not until the grid-controlled mercury rectifier tube was developed that a basis was provided for improving the voltage regulator. Electronic voltage regulators provide practically instantaneous response without the use of moving parts.

INTRODUCTION

The increasing need for an automatic voltage regulator to meet the exacting requirements of industrial and laboratory service has led to innumerable attempts to produce a device which will keep the terminal voltage of an alternator constant as the load is varied. If an alternator has its field current adjusted so as to supply rated voltage at no-load and rated frequency, the terminal voltage decreases as resistive or inductive loads are applied and increases as capacitive loads are applied to the machine. In order to prevent this the generated voltage of the machine must be controlled by controlling the field current to compensate for the variable impedance drop and the variable demagnetizing effects.

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The purpose of this paper is to discuss the design, construction and performance of an electronic voltage regulator for a 12.5-kva laboratory alternator. The alternator is to be used as a power supply for undergraduate experiments on a 5-kva synchronous motor. The generator is driven by a 15-hp, compound-wound direct current motor. The synchronous motor experiments require constant voltage for loads up to 7.5-kva for a range of power factor between 0.5 lagging and 0.5 leading. This essay includes a brief survey of voltage regulator circuits as well as the solution of the above problem.

A BRIEF SURVEY OF AVAILABLE CIRCUIT ARRANGEMENTS FOR ELECTRONIC VOLTAGE REGULATORS

The gas-filled triode or thyratron is the most important component of an electronic voltage regulator. Its usefulness lies in its low, constant, internal voltage drop and the resulting high circuit efficiency for large currents. However, the ionization of the gas which permits this low drop also prevents the control grid from stopping the flow after it has once begun. Therefore, the usual application of thyratrons is on an alternating current system where the periodic reversal of the anode voltage permits deionization and a chance for the grid to regain control. After current has ceased flowing upon the reversal of the anode voltage and subsequent deionization, a negative grid will prevent its restarting even though the anode has again become positive. It is possible to operate the grid of a thyratron from a direct current supply, but to obtain smooth control, it is necessary to use firing circuits which operate wholly or partially from the same alternating current supply used for the anode circuit.

The basic parts of a voltage regulator are:

(1) Voltage-sensitive circuit

(2) Control circuit

(3) Thyratron circuit

(4) Stabilizing circuit

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The basic parts of a voltage regulator are:

(1) Voltage-sensitive element

(2) Control circuit

(3) Thyratron circuit

(4) Anticipating circuit

Probably the first voltage sensitive circuit used in an electronic voltage regulator was the non-linear bridge. This bridge has been used in many forms, but the most common appears to be the lamp bridge. This is shown in Fig.1 where R_1 and R_2 are tungsten lamps and R_3 and R_4 are carbon lamps. It operates on the principle that the resistance of tungsten increases with increasing temperature while the resistance of carbon decreases with increasing temperature. Therefore there is only one value of applied voltage for which the bridge is balanced. The output voltage for an input less than that required for balance is out of phase by 180° to the output for an input voltage greater than the balance value. This circuit has been used successfully by Weinland[2] and Benson[6,7]. A variation of this bridge whereby linear resistors replaces lamps in opposite arms, as R_3 and R_4, has been used by Hull[1] and Richter[13]. Another type of non-linear bridge was used by Whipple and Jacobsen[4] and is shown in Fig.2. The values of the circuit parameters were such that the output was extremely sensitive at the value of voltage to be regulated (120 volts) as shown in Fig. 3.

Gullikson[3] describes another type of voltage-sensitive circuit in which the terminal voltage of the alternator supplies voltage through a transformer to the [illegible]

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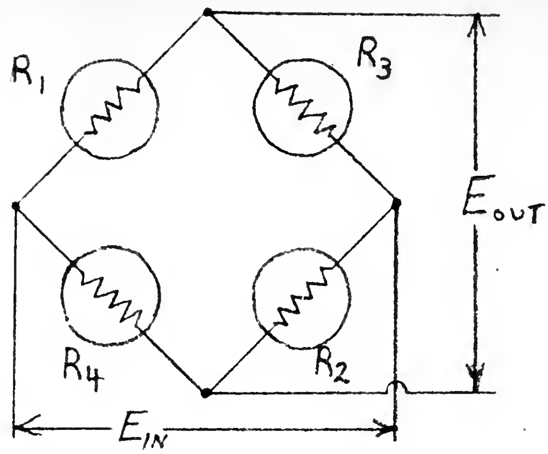


FIG. 1 - NON-LINEAR LAMP BRIDGE

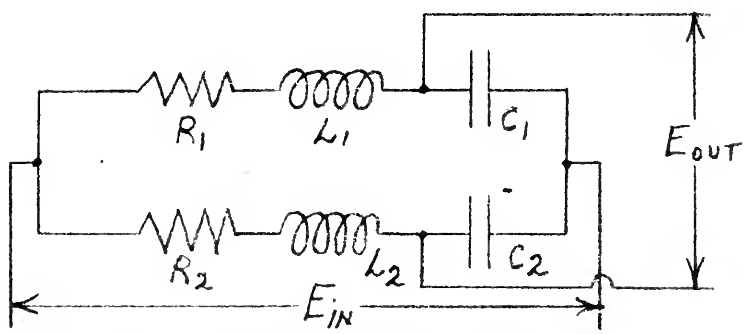
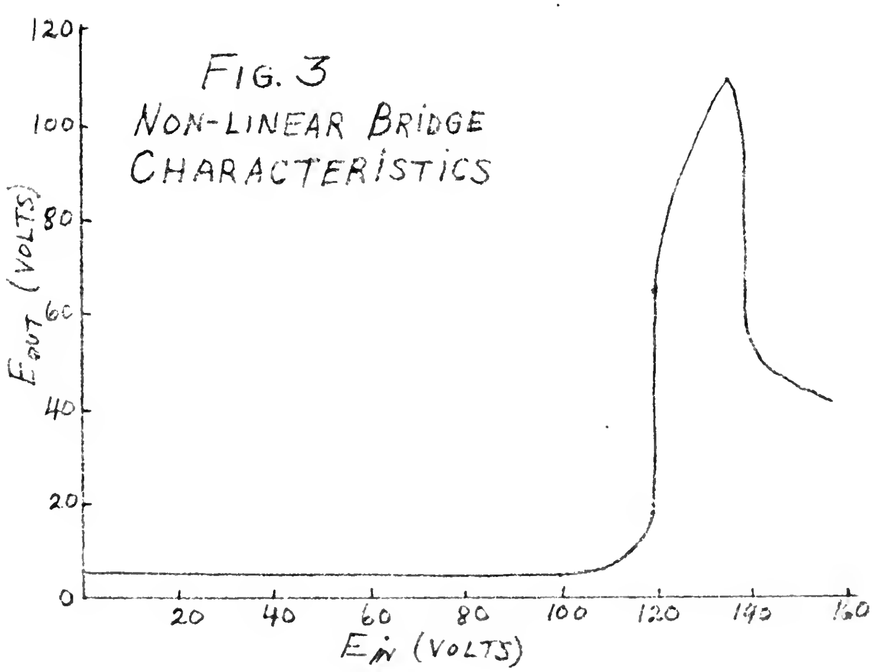


FIG. 2 - NON-LINEAR BRIDGE



sten filament of a high vacuum diode, operating at an anode voltage which exceeds the saturating voltage so that anode current will be controlled by the filament temperature and consequently the filament voltage. The disadvantage of this circuit and the lamp bridge circuit is that response is not instantaneous due to a small thermal lag.

The most popular voltage-sensitive device is the full-wave rectifier and filter which detects instantly any change in the alternator terminal voltage, the output being direct current. This circuit is used for controlling the grid circuit of a thyratron by shifting the phase of the grid voltage as will be explained later.

There are three fundamental methods of controlling the grids of thyratrons in voltage regulators using alternating current.

(1) Phase shift of the grid voltage (with respect to the anode voltage).

(2) A fixed phase alternating voltage superimposed upon a variable unidirectional voltage.

(3) The magnitude method which is associated with the lamp bridge.

The phase shifter usually consists of a resistance-reactance circuit. Phase shift is obtained by varying the resistance which [illegible] be a triode [illegible]

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is varied by a unidirectional voltage proportional to the alternator output. Likewise the reactance may be varied (and this is commonly done) by the use of a saturable reactor whose saturation is likewise controlled by a direct current voltage similar to the above. Various phase control circuits are explained in papers by Cockrell[8], Chin[9], May, Reich, Skalnik[10], and Annett[12].

Cockrell[8] describes a fixed a.c. with a variable d.c. circuit in which an alternating current of fixed amplitude from the anode supply is made to lag the anode voltage by 90° and the direct current bias is varied in proportion to the terminal voltage. As shown in Fig. 4 this method permits control of the thyratron throughout the positive half of the cycle. At least one of the commercially produced voltage regulators [11] employs this method of grid control.

The output of the lamp bridge may be applied directly to the grid of the thyratron and 180° out of phase with the anode voltage, the firing being determined by the magnitude of the grid voltage. This is not desirable due to the fact that the grid has control for only half of the positive half of the cycle as shown in Fig. 5(c). Heinland[5] and Benson[6,7] used an RC phase shift network such that the grid voltage lagged the anode voltage by an angle slightly less than 180° and obtained a greater degree of

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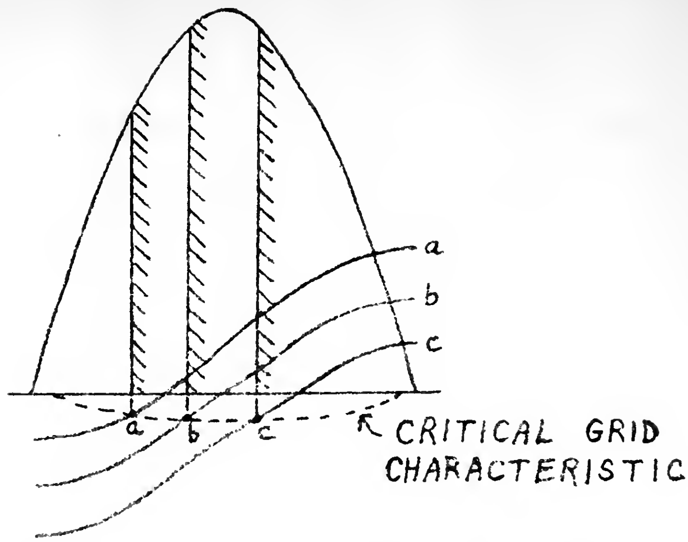

FIG. 4 - GRID CONTROL BY FIXED A-C AND VARIABLE D-C. SHADED AREA INDICATES TUBE CONDUCTION.

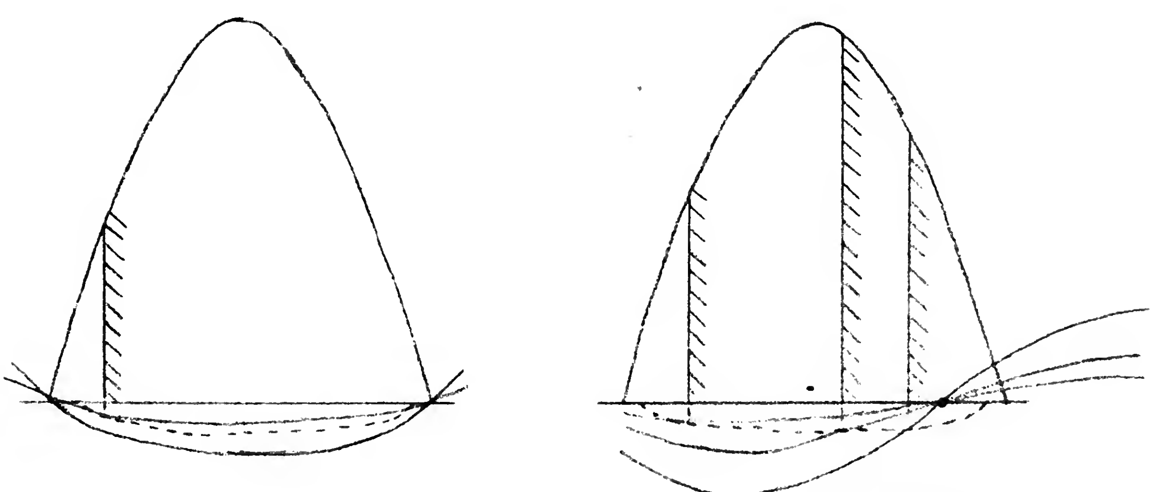

FIG. 5(a) FIG. 5(b)

MAGNITUDE METHOD OF GRID CONTROL

control as shown in Fig. 5(b). Weinland[2] also obtained greater sensitivity by using a center-tapped step-up transformer and controlling the grids of two thyratrons connected as a full wave rectifier.

The thyratron circuit consists of the anode supply voltage, the thyratron tube or tubes and the load. Since much better control is obtained when the grid and anode voltages are from the same source, the alternator usually supplies the anode voltage. However, the commercial regulator described in reference 11 is an exception and uses a separate three-phase voltage supply and three thyratrons.

Alternators are usually excited by a small direct current exciter whose rotor is coupled to the alternator shaft. The load in this case is the field circuit of the exciter which requires a great deal less current than the alternator field. Since the current rating of the tubes of a voltage regulator is limited to a few amperes, an exciter is a necessity when regulating the terminal voltage of large alternators. The field current of the exciter and alternator may be controlled by connecting the output of the regulator directly across the field winding, aiding or opposing, or may be connected across the field rheostat[4].

When an exciter is used, the time constants of both the exciter and alternator fields enter and hunting of the terminal voltage may result, necessitating an antihunting

control as shown in Fig. 3(b). Reinlund[3] also obtained greater sensitivity by using a center-tapped step-up transformer and controlling the grids of two thyratrons connected as a full wave rectifier.

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When an exciter is used, the field current [illegible] both the exciter and alternator fields [illegible] the terminal voltage [illegible]

circuit[6,11]. This is usually an RC circuit connected directly across the alternator field. Current flows through this circuit only when there is a change in the voltage across the field, resulting in a momentary potential rise or drop across the resistance. This momentary potential is applied to the grid of the thyratron in the correct direction to prevent hunting. Weinland[2] found that an antihunting circuit was usually unnecessary when the alternator field was controlled directly.

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CHARACTERISTICS OF THE ALTERNATOR

The alternator selected for voltage regulation was the Model 11G491 Type ATB manufactured by the General Electric Company (see Fig. 12(a)). It is rated at 12.5 - kva, 208 volts, 34.7 amperes, 3-phase at 60 cycles. Field excitation is obtained from a 250 volt d.c. bus. The prime mover is a General Electric Model 35A1801 Type CD compound-wound direct current motor rated at 15-hp, 250 volts, 51 amperes at 1200 RPM. The output of the alternator is not a pure sine wave, but has a pronounced 23rd harmonic ripple. It would have been desirable for the alternator to be driven by a synchronous motor to provide constant speed and consequently a constant frequency output from the alternator. Automatic speed control of the motor will be applied later.

There was no data available on the characteristics of this machine, so it was necessary to conduct tests for the open-circuit and short-circuit characteristics. The results are shown in Fig. 6. These tests were conducted by the usual method described in most standard text books on the subject. In addition the ohmic resistance of the field was measured as 69.5 ohms and the ohmic resistance of the armature as .053 ohms per phase. These values were obtained by the voltmeter-ammeter method.

CHARACTERISTICS OF THE ALTERNATOR

The alternator selected for voltage regulation was the Model 110491 type ATB manufactured by the General Electric Company (see Fig. 1(b)). It is rated at 12.5 kva, 208 volts, 34.7 amperes, 3-phase at 60 cycles. Field excitation is obtained from a 250 volt d.c. bus. The prime mover is a General Electric Model 5CA1601 Type CD compound-wound direct current motor rated at 15-hp, 230 volts, 51 amperes at 1200 RPM. The output of the alternator is not a pure sine wave, but has a pronounced 3rd harmonic ripple. It would have been desirable for the alternator to be driven by a synchronous motor to provide constant speed and consequently a constant frequency output from the alternator. Automatic speed control of the motor will be applied later.

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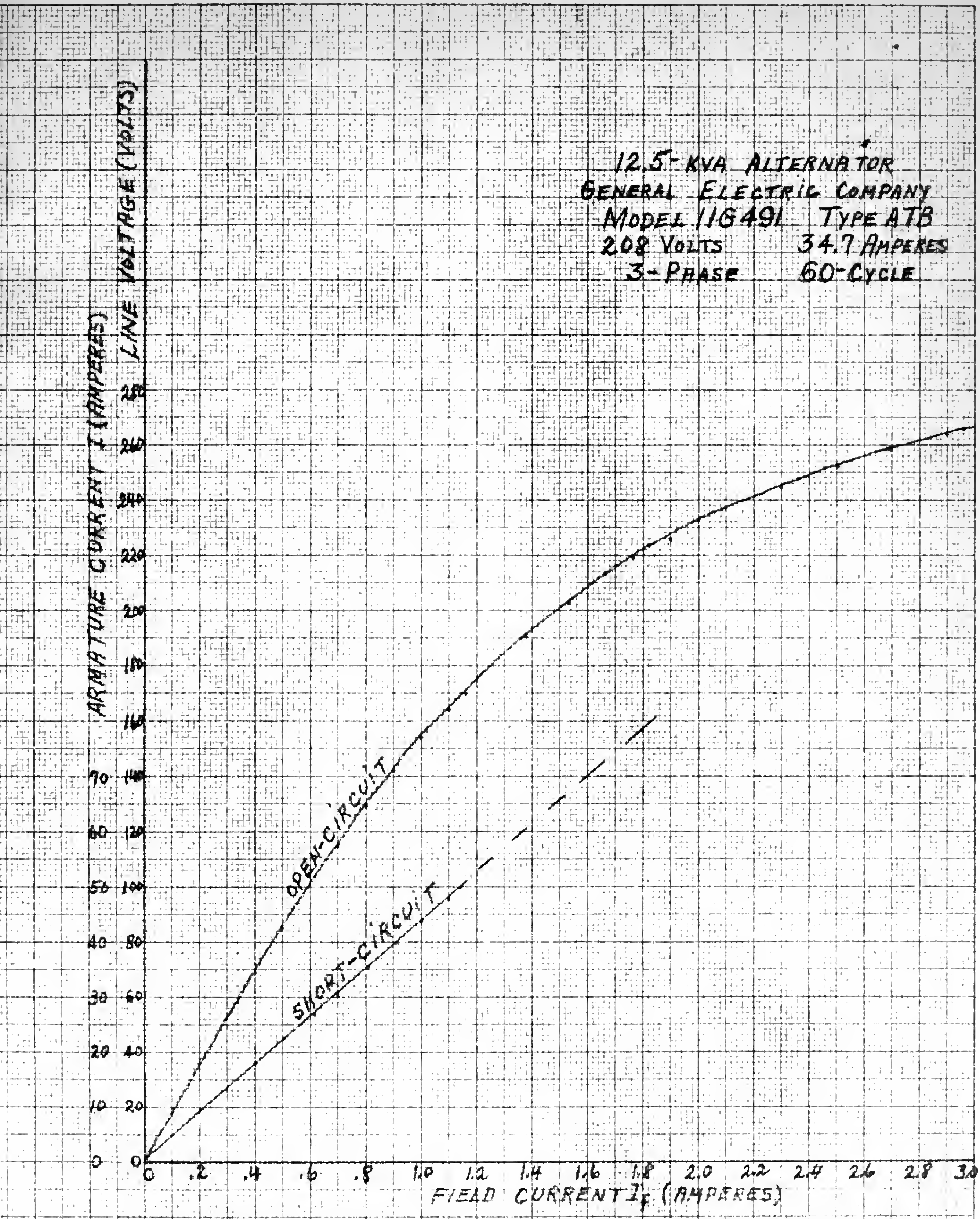

FIG. 6-OPEN-CIRCUIT AND SHORT-CIRCUIT CHARACTERISTICS OF 12.5-KVA ALTERNATOR.

For design purposes the Synchronous-impedance or Pessimistic Method is satisfactory for calculating the regulation of the alternator since it gives a value of regulation poorer than the actual regulation. The synchronous impedance is calculated at the highest possible value of armature current, usually at twice rated current. From Fig. 6 the field current corresponding to twice rated current is 1.58 amps and the open-circuit voltage corresponding to this value of field current is 206 volts. If it is assumed that this voltage is being used entirely in sending twice rated current through the armature impedance, then the synchronous impedance per phase, Z_s, may be calculated as equal to $\frac{206}{\sqrt{3}\ 69.5} = 1.71$ ohms. This is made up of two components, the effective resistance R_e and the synchronous reactance, X_s. Therefore $X_s = \sqrt{Z_s^2 - R_e^2}$ and since R_e is very small, X_s may be assumed to be equal to Z_s.

The regulation of this machine supplying a 7.5-kva load at unity power factor is calculated as follows:

$I = \frac{7500}{\sqrt{3}\ 208} = 20.8$ amps. $V/\text{phase} = \frac{208}{\sqrt{3}} = 120$ volts.

R_e is assumed to be 1.4 times the ohmic resistance = 1.4 x .053 = .074 ohms.

$E = \sqrt{(V/\text{phase} + IR_e)^2 + (IX_s)^2}$

For design purposes the synchronous-impedance or Pessimistic Method is satisfactory for calculating the regulation of the alternator since it gives a value of regulation poorer than the actual regulation. The synchronous impedance is calculated at the highest possible value of armature current, usually at twice rated current. From Fig. 6 the field current corresponding to twice rated current is 1.88 amps and the open-circuit voltage corresponding to this value of field current is 206 volts. It is assumed that this voltage is being used entirely in sending twice rated current through the armature impedance, then the synchronous impedance per phase, Z_s, may be calculated as equal to $\frac{206}{\sqrt{3}\ 69.6}$ = 1.71 ohms. This is made up of two components, the effective resistance R_e and the synchronous reactance, X_s. Therefore $X_s = \sqrt{Z_s^2 - R_e^2}$ and since R_e is very small, X_s may be assumed to be equal to Z_s.

The regulation of this machine at [illegible] load at unity power factor is calculated as follows:

$I =$ [illegible] $=$ [illegible] volts.

R_e is assumed to be 1.6 times [illegible] $=$

1.6 × [illegible] = .076 ohm.

$= \sqrt{(V \cos\theta + I R_e)^2 +}$ [illegible]

$$E = \sqrt{(120 + 20.8 \times .074)^2 + (20.8 \times 1.71)^2}$$

$$E = \sqrt{(121.54)^2 + (35.6)^2} = \sqrt{14780 + 1268}$$

$$E = \sqrt{16048} = 126.8 \text{ volts}$$

$$\text{Regulation} = \frac{126.8 - 120}{120} \times 100 = 5.65\%$$

For 7.5-kva load at 0.5 power factor, lagging

$$E = \sqrt{(V\cos\theta + IR_e)^2 + (V\sin\theta + I\lambda_s)^2}$$

$$E = \sqrt{(120 \times .5 + 20.8 \times .074)^2 + (120 \times .866 + 20.8 \times 1.71)^2}$$

$$E = \sqrt{(60 + 1.54)^2 + (104 + 35.6)^2} = \sqrt{3800 + 19500}$$

$$E = \sqrt{23300} = 152.5 \text{ volts}$$

$$\text{Regulation} = \frac{152.5 - 120}{120} \times 100 = 27.1\%$$

For 7.5-kva load at 0.5 power factor, leading

$$E = \sqrt{(V\cos\theta + IR_e)^2 + (V\sin\theta - I\lambda_s)^2}$$

$$E = \sqrt{3800 + (104 - 35.6)^2} = \sqrt{3800 + (68.4)^2}$$

$$E = \sqrt{3800 + 4670} = \sqrt{8470} = 92 \text{ volts}$$

$$\text{Regulation} = \frac{92 - 120}{120} \times 100 = -23.3\%$$

ESTABLISHMENT OF THE LOAD RANGE AND RANGE OF POWER FACTOR

The synchronous motors which will receive their power from this alternator are rated at 5-kva and it is not anticipated to use more than one as a load on this alternator at any one time. The synchronous motor will seldom be required to operate with more than 50% overload so the load range was set at 7.5-kva.

The alternator field is rated at 2.5 amperes and it should not be operated at a value very much higher than this for any long period of time. However, it is believed that a maximum field current of 3 amperes would not be harmful to the field winding.

In the preceding section the generated phase voltage was calculated for a 7.5-kva load at 0.5 power factor, lagging and leading. The values correspond to line voltages of 264 volts for the lagging case and [illegible] volts for the leading case. From the characteristic curves of Fig. 6 these require field currents of 2.9 and 1.05 amperes respectively. Since the maximum field current has been set at 3 amperes, the extreme lagging power factor that can be obtained is slightly less than 0.5. There is no limit for leading power factor at 7.5-kva, but it is not anticipated that it will be less than 0.5.

DETERMINATION OF THE LOAD RANGE AND RANGE OF POWER FACTOR

The synchronous motors which will receive their power from this alternator are rated at 5-kva and it is not anticipated to use more than one as a load on this alternator at any one time. The synchronous motor will seldom be required to operate with more than 50% overload so the load range was set at 7.5-kva.

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In the preceding section the generated phase voltage was calculated for a 7.5-kva load at 0.8 power factor, lagging and leading. The values correspond to line voltages of 164 volts for the lagging case and 139 volts for the leading case. From the characteristic curves it is shown [illegible] field currents of [illegible] and [illegible] respectively. [illegible]

In order to see more clearly the load and power factor ranges of the alternator for a maximum field current of 3 amperes, a simple diagram may be constructed in which the armature resistance effect is neglected as in Fig. 7. Thus it is seen that approximately full load may be obtained at 0.9 lagging, 10-kva at 0.8 lagging, 9-kva at 0.7 lagging and 8.5-kva at 0.6 lagging. Therefore, a regulator that is capable of supplying current up to 3 amperes will give regulation over a fairly wide range of loads and power factors.

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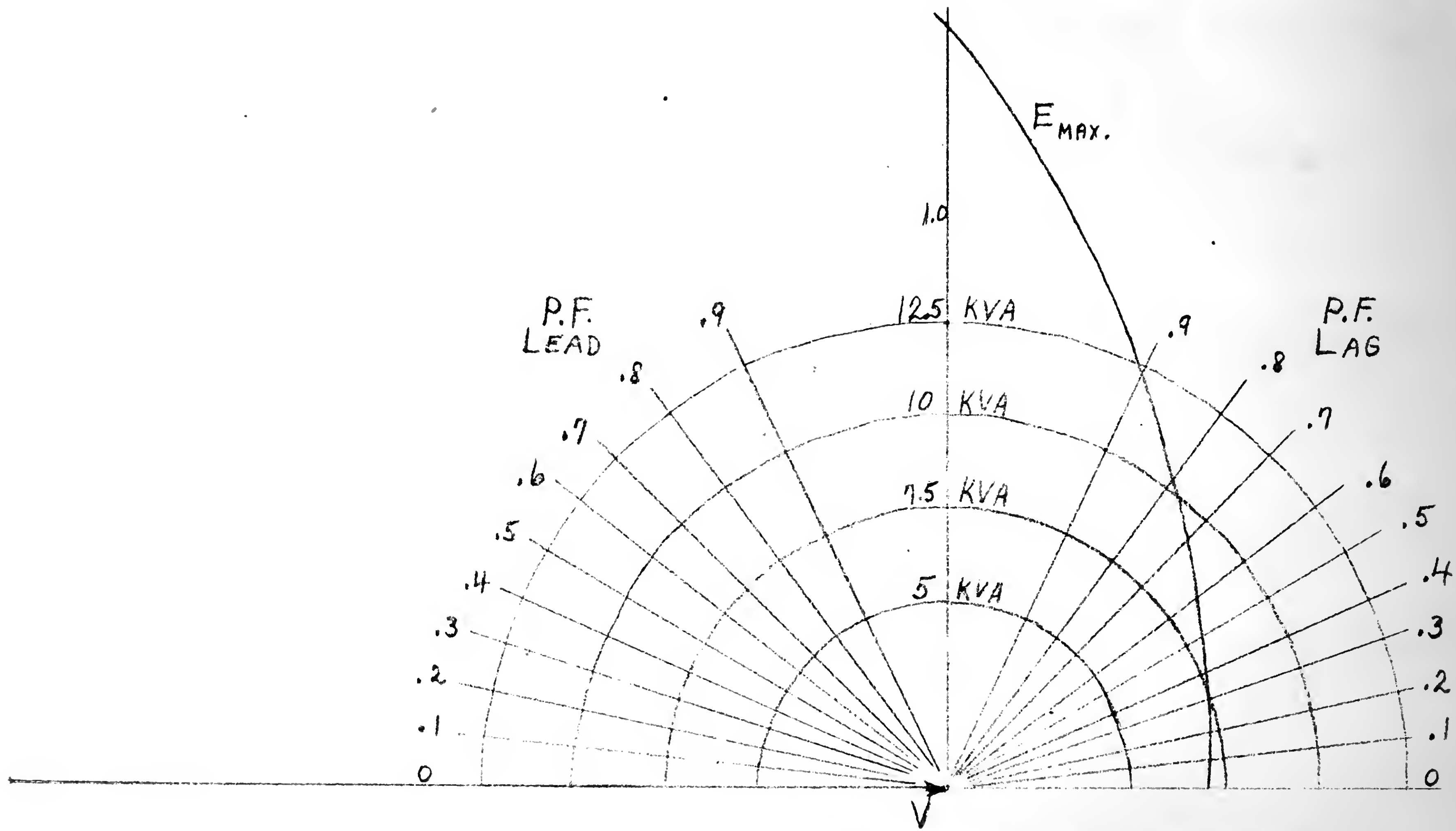

FIG. 7. – DIAGRAM OF LOAD AND POWER FACTOR RANGE FOR MAXIMUM FIELD CURRENT OF 3 AMPERES. (APPROXIMATE SINCE EFFECT OF ARMATURE RESISTANCE IS NEGLECTED).

SELECTION OF CIRCUIT ARRANGEMENTS

It was desired that the circuit arrangement of the voltage regulator contain as few components as possible and yet maintain the terminal voltage nearly constant over the range determined in the preceding section. The components should be of the standard types available at an economical price, but should be rugged enough such that replacement will be required only after long periods of use. Furthermore, the necessary adjustments for proper operation of the regulator should be few and simple.

As explained in a previous section, better regulation can be obtained when the regulator is operated from the regulated supply voltage. In order to prevent possible distortion of the alternator terminal voltage, the regulator should conduct current on both positive and negative halves of the cycle. Two thyratrons connected as a full wave rectifier form a convenient arrangement and in addition this produces a rectified current with a wave form which is much more desirable than that obtained from a half-wave arrangement. Since the maximum average current rating of thyratrons seldom exceeds [illegible].5 amperes and the current requirement of the regulator is [illegible] amperes, it would be impossible to manage with only one tube, even if half-wave rectification proved to be satisfactory.

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In view of the fact that the regulator is required to regulate the terminal voltage when the load draws a leading current, a condition which may require a smaller field current than is required at no-load, the regulator must supply all current necessary in excess of that required at a power factor of 0.5, leading. The best solution appears to be to connect the output of the regulator directly across the alternator field, aiding the excitation current and to decrease the value of field current supplied by the D.C.bus by means of the field rheostat after the regulator has been placed in operation.

The lamp bridge is the simplest and cheapest to construct of the existing voltage-sensitive circuits. It has the added advantage that the output may be applied directly to the grid of the thyratron through a center-tapped transformer in the case of full-wave rectification without the use of a phase shifting circuit, as will be explained later.

This arrangement does not require a battery for grid bias or as a reference voltage as many existing regulators do. This eliminates another item of initial expense and cost of maintenance.

In view of Weinland's findings that an [illegible] circuit is not necessary when the regulator controls the alternator field directly, this circuit was not included.

In view of the fact that the regulator is required to regulate the terminal voltage when the load draws a leading current, a condition which may require a smaller field current than is required at no-load, the regulator must supply all current necessary in excess of that required at a power factor of 0.8, leading. The best solution appears to be to connect the output of the regulator directly across the alternator field, giving the excitation current and to decrease the value of field current supplied by the D.C. bus by means of the field rheostat after the regulator has been placed in operation.

The lamp bridge is the simplest and cheapest to construct of the existing voltage-sensitive circuits. It has the added advantage that the output can be applied directly to the grid of the thyratron through a center-tapped transformer in the case of full-wave rectification without the use of a phase shifting circuit, as will be explained later.

This arrangement does not require a battery for grid bias or as a reference voltage as do [illegible] existing regulators do. This eliminates the [illegible] expense and cost of maintenance.

In view of [illegible]

circuit is not necessary [illegible]

alternator [illegible]

DESIGN OF THE CIRCUIT

The alternator armature is Y-connected with all four leads terminating at the panel board and the neutral is not grounded. The line voltage is 208 volts and the phase voltage is 120 volts. This value of phase voltage allows the standard filament transformers that are commercially available to be used for heating the filaments of the thyratrons. As shown in Fig. 8 there are voltages of a number of different phase relations available and those differing by 150° may be used to good advantage as the anode supply voltage and the voltage input to the lamp bridge, thus eliminating the necessity of a phase shift network.

Voltage-sensitive circuit:

The voltage vs. resistance characteristics of carbon and tungsten lamps are reproduced in Fig. 9. The point of intersection of the curves of a tungsten and carbon lamp indicates the voltage at which the resistances of the two lamps are equal. If these lamps were used in the lamp bridge, twice this voltage would be the value required to balance the bridge. Also the greater the angle of intersection the more sensitive the bridge will be. Since it is desired to use the phase voltage of 120 volts as the input to the bridge, the 25 watt tungsten and 120

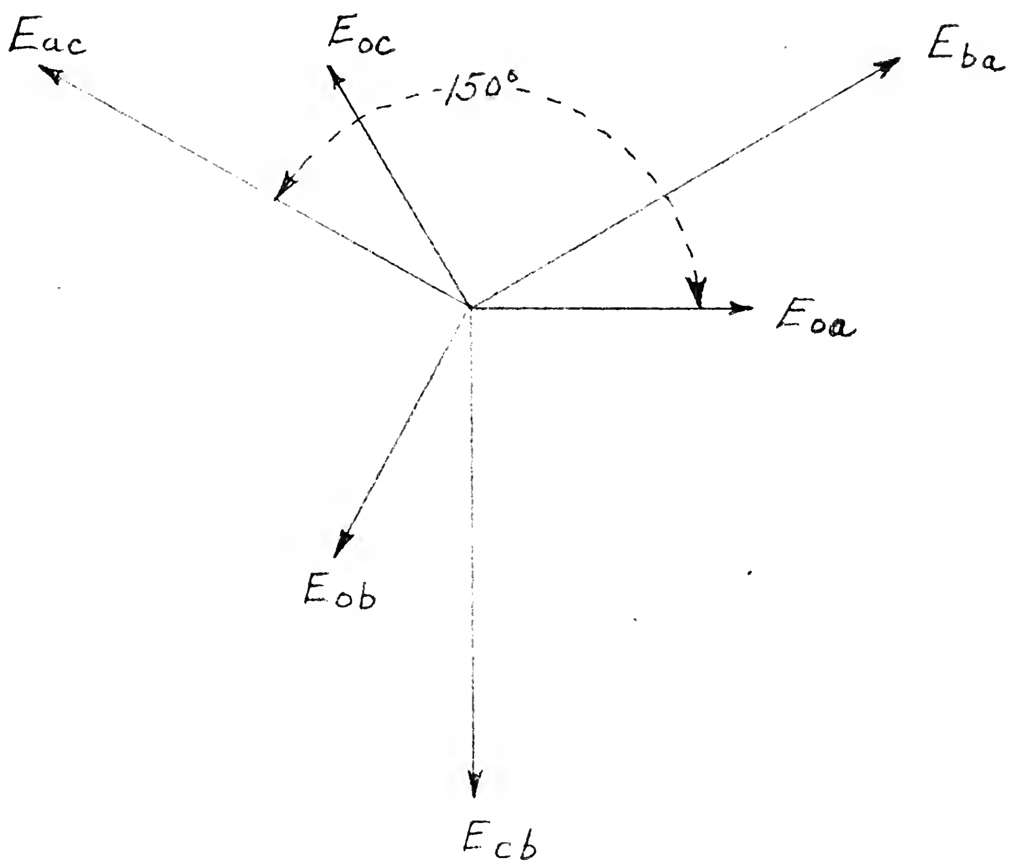

FIG. 8 – PHASE RELATION OF LINE AND PHASE VOLTAGES OF ALTERNATOR.

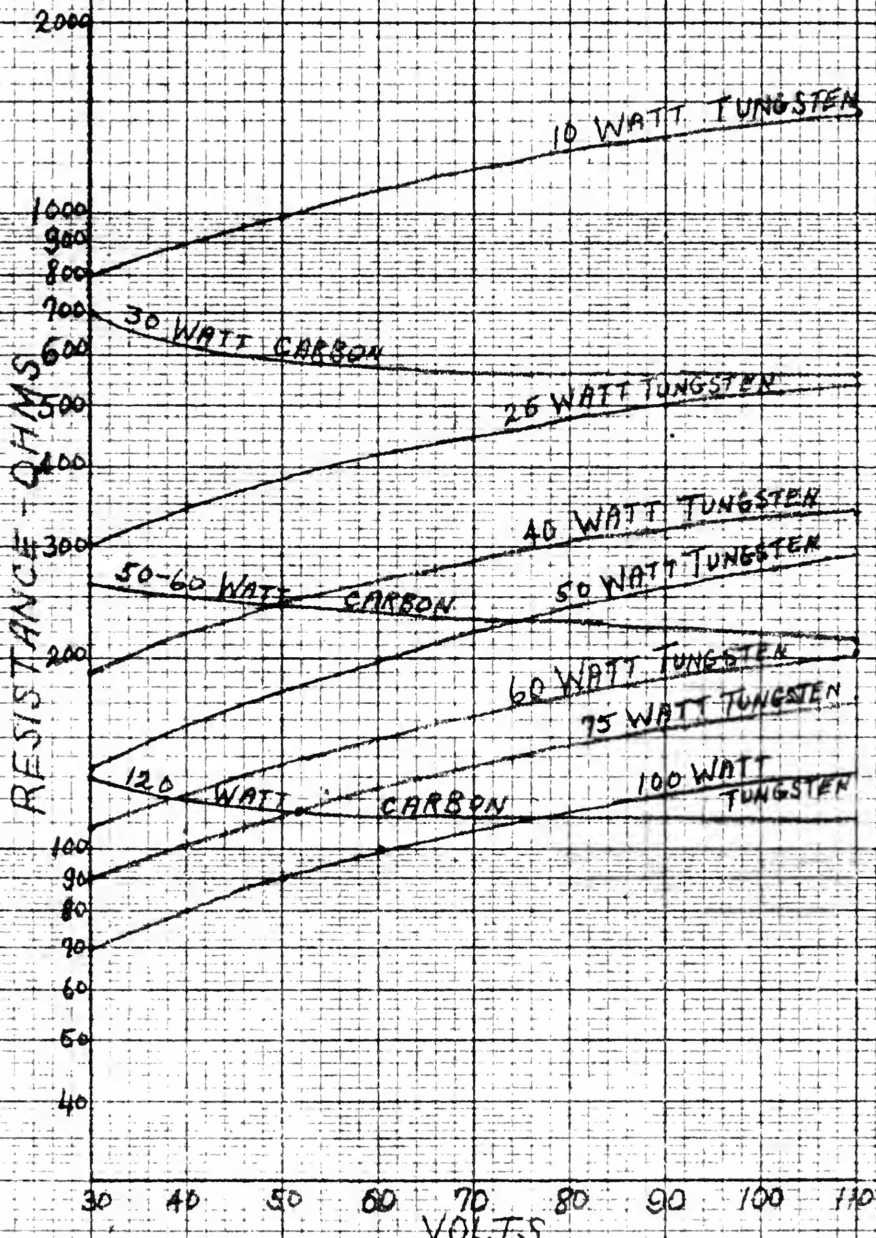

Fig. 9 - VOLTAGE vs. RESISTANCE CHARACTERISTICS OF CARBON AND TUNGSTEN LAMPS.

watt or 32 C.P. carbon combination appears to be the best, giving a balance at 103 volts. The voltage characteristics of this bridge is shown in Fig. 10. At balance each lamp requires .45 amperes or the total current required from the alternator is .9 amperes. Therefore a standard 25 ohm, 25 watt potentiometer in the voltage sensitive circuit is sufficient to reduce the phase voltage to the bridge operating voltage.

<u>Thyratron Circuit:</u>

The FG-57 thyratron appears to be satisfactory for this problem. It is a mercury-vapor negative-grid rectifier rated at 2.5 amperes average current, 15 amperes peak current and 200 amperes maximum surge current. It can withstand a maximum peak anode and inverse peak voltage of 1000 volts and the heater requires 4.5 amperes at 5 volts. Prior to operating this tube it is recommended that the heaters be operated for 5 minutes. The normal peak voltage drop across the tube is 16 volts.

If the phase voltage, E_{oa}, is applied to the lamp bridge, then the line voltage, E_{ac}, which leads E_{oa} by 150^{o}, is required for the thyratron anode supply voltage. The anode voltage is calculated as follows:

Maximum average voltage required to deliver 5.0 amperes to a field of 69.5 ohms is

watt or 32 C.P., carbon combination appears to be the best, giving a balance at 108 volts. The voltage characteristics of this bridge is shown in Fig. 19. At balance each lamp requires .45 amperes or the total current required from the alternator is .9 amperes. Therefore a standard 25 ohm, 25 watt potentiometer in the voltage sensitive circuit is sufficient to reduce the phase voltage to the bridge operating voltage.

Thyratron Circuits:

The FG-57 thyratron appears to be satisfactory for this problem. It is a mercury-vapor negative-grid rectifier rated at [illegible] amperes average current, 15 amperes peak current and 200 amperes maximum surge current. It can withstand a maximum [illegible] and inverse peak voltage of 1000 volts and the heater requires [illegible] amperes at 5 volts. Prior to operating this tube it is recommended that the heater be on for [illegible] minutes. The peak voltage drop across the tube is 16 volts.

If the anode voltage, Ea, is applied to the lamp bridge then the line voltage, Ega which leads Ea by 100°, is required for the thyratron anode supply voltage. The anode voltage is calculated as follows:

Maximum average voltage required to deliver 2.5 amperes to a field of 29.5 ohms is

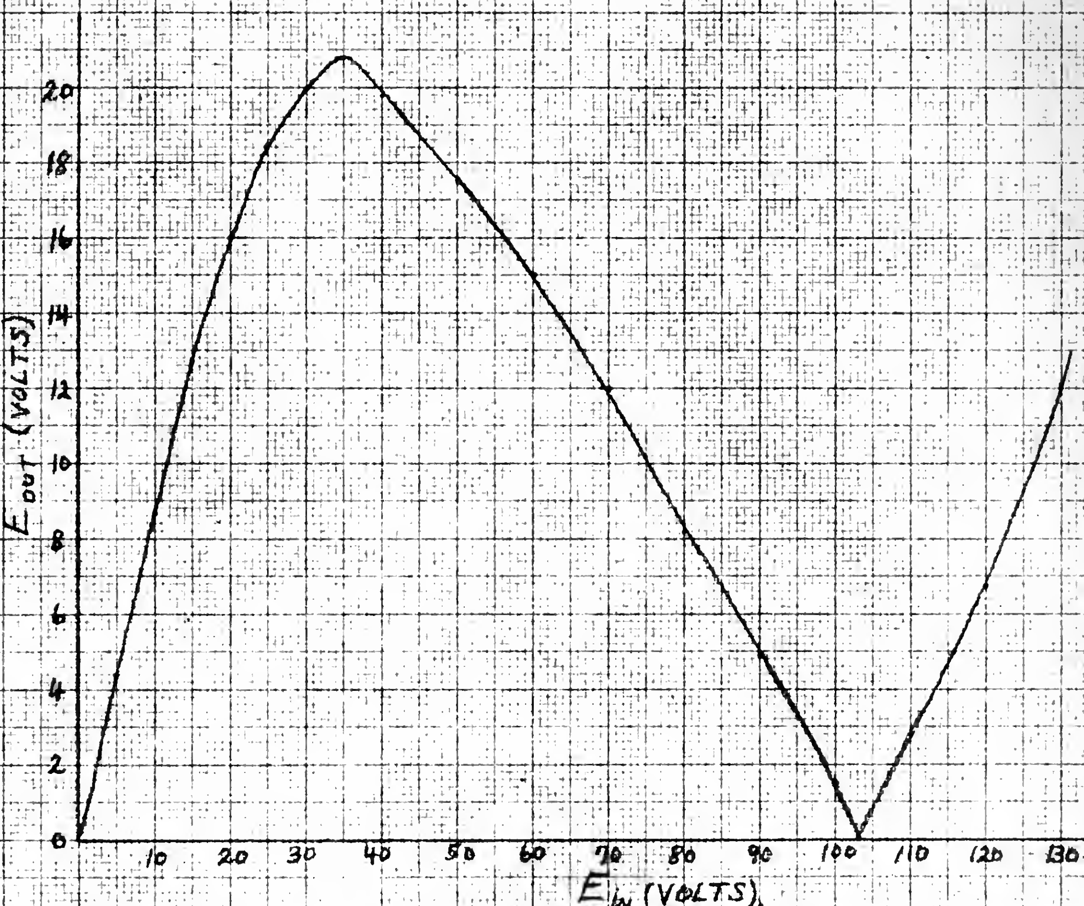

FIG. 10 - VOLTAGE CHARACTERISTICS OF 75 WATT TUNGSTEN AND 120 WATT CARBON LAMP BRIDGE.

$$3.0 \times 69.5 = 208 \text{ volts}$$

Amplitude of half sine wave required for this maximum average voltage is

$$E_m = \frac{\pi}{2} E_{av} = \frac{\pi}{2} \times 208 = 327 \text{ volts}$$

The rms voltage is $\frac{327}{\sqrt{2}} = 231$ volts.

The expected drop across the tube is $\frac{16}{\sqrt{2}} = 11.3$ volts, giving a value of 242.3 volts rms as the required anode supply voltage. Since the thyratrons are to be operated as a full wave rectifier, the secondary winding of the transformer whose primary is connected across the 208 volt line voltage, ac, must deliver twice the above voltage or 484.6 volts, center-tapped. A 1-kva, 220:660-volt, center-tapped transformer should be satisfactory for this problem.

Grid Control Circuit:

The grid control circuit consists of a small 1:5 step-up, center-tapped transformer with the primary connected across the output of the lamp bridge and the secondary terminals each connected in series with a 47,000 ohm resistor to the grids of the thyratrons in such a manner that each grid voltage lags its respective anode voltage by 150°. The center tap of the secondary is connected to the two thyratron cathodes. This arrangement permits grid control similar to that shown in Fig. 5(b). The purpose of the 47,000 ohm resistors is to restrict the flow of grid current.

$$3.0 \times 69.3 = 208 \text{ volts}$$

Amplitude of half sine wave required for this maximum average voltage is

$$E_m = \frac{\pi}{2} E_{av} = \frac{\pi}{2} \times 208 = 327 \text{ volts}$$

The rms voltage is $\frac{327}{\sqrt{2}} = 231$ volts.

The expected drop across the tube is $\frac{16}{\sqrt{2}} = 11.3$ volts, giving a value of 242.3 volts rms as the required anode supply voltage. Since the thyratrons are to be operated as a full wave rectifier, the secondary winding of the transformer whose primary is connected across the 208 volt line voltage, so, must deliver twice the above voltage or 484.6 volts, center-tapped. A 1-kva, 220:600-volt, center-tapped transformer should be satisfactory for this problem.

Grid Control Circuit:

The grid control circuit consists of a small 1:3 step-up, center-tapped transformer with the primary connected across the output of the lamp bridge and the secondary terminals each connected in series with a 47,000 ohm resistor to the grids of the thyratrons in such a manner that each grid voltage lags its own anode voltage by [illegible]. The center tap of the secondary is connected to the [illegible] thyratron cathodes. This [illegible] similar to that shown in Fig. [illegible] 47,000 ohm resistor is to restrict [illegible] rent.

Heater voltage may be obtained from the alternator phase voltage or from the 115-120 volt commercial supply through a standard filament transformer rated at 5 volts and at least 9 amperes. A 25 ohm, 25 watt potentiometer in the primary of the filament transformer may be necessary to produce an output of 5 volts when the phase voltage is used. The complete circuit diagram is shown in Fig. 11.

Heater voltage may be obtained from the alternator phase voltage or from the 115-130 volt commercial supply through a standard filament transformer rated at 5 volts and at least 9 amperes. A 25 ohm, 25 watt potentiometer in the primary of the filament transformer may be necessary to produce an output of 5 volts when the phase voltage is used. The complete circuit diagram is shown in Fig. 11.

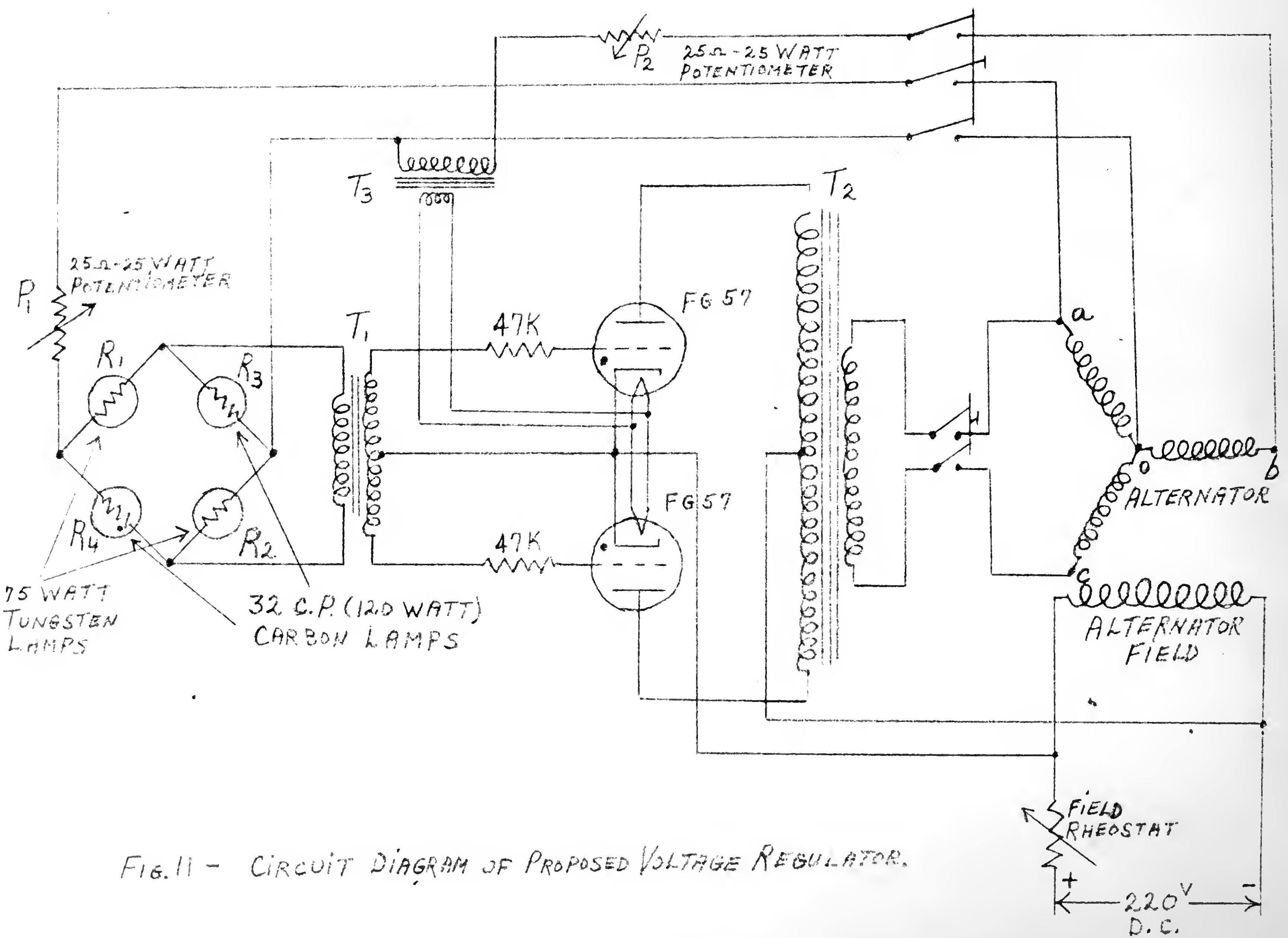

Fig. 11 - Circuit Diagram of Proposed Voltage Regulator.

CONSTRUCTION

The regulator was constructed on a breadboard, a photograph of which is shown in Fig. 12 (b). All components used were as designed, except the anode supply voltage transformer T_2. A 230:460-volt step-up, center-tapped transformer rated at 1-kva was available and in view of the fact that the design of the circuit was based on the pessimistic method of calculating voltage regulation, it was hoped that this transformer would be adequate for testing the circuit. Performance tests later proved that it was adequate for regulation between the range of 0.5 lagging and 0.5 leading with a 7.5-kva load, but would supply only 2.65 amperes to the alternator field instead of the desired 3.0 amperes.

The heater and cathode of the FG-57 thyratron tube are connected internally. Since these tubes have their cathodes connected at a common point in this circuit, care must be taken to insure that the heater terminals of one tube are connected to the corresponding terminals of the second tube to prevent a short circuit.

CONSTRUCTION

The regulator was constructed on a breadboard, a photograph of which is shown in Fig. 12 (b). All components used were as designed, except the anode supply voltage transformer T_p. A 230:460-volt step-up, center-tapped transformer rated at 1-kva was available and in view of the fact that the design of the circuit was based on the pessimistic method of calculating voltage regulation, it was hoped that this transformer would be adequate for testing the circuit. Performance tests later proved that it was adequate for regulation between the range of 0.5 lagging and 0.8 leading with a 7.5-kva load, but would supply only 1.65 amperes to the alternator field instead of the desired 2.0 amperes.

The heater and cathode of the 5-U4 G rectifier tube are connected internally. Since these tubes have their cathodes connected [illegible] very much be taken to ensure that [illegible] tube are each other [illegible] secondary [illegible].

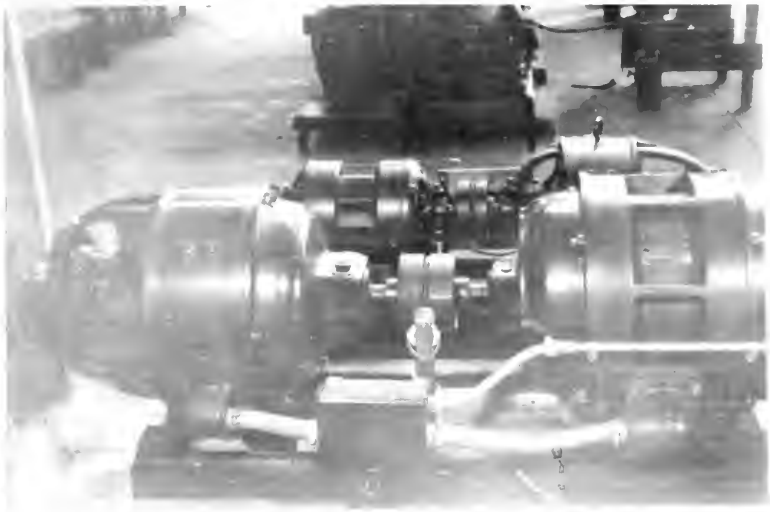

Fig.12(a) - 12.5-kva General Electric alternator and motor.

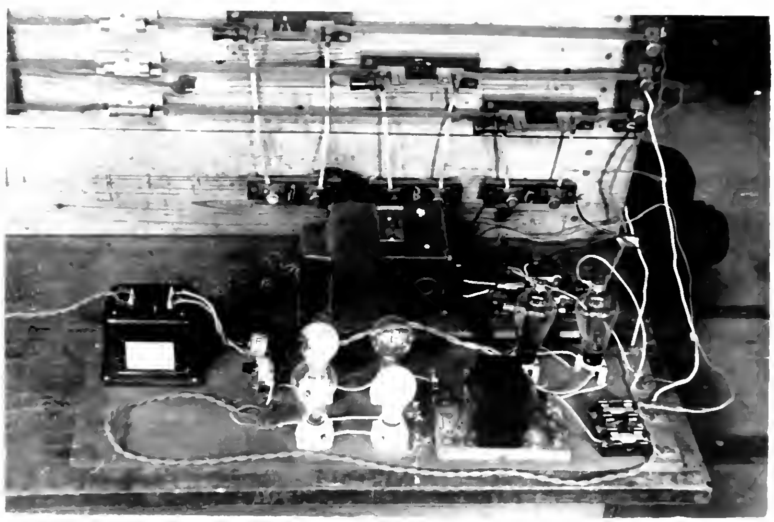

Fig. 12(b) - Breadboard arrangement of voltage regulator.

PERFORMANCE TESTS

In order to test performance, the regulator was placed in operation and the field rheostat of the alternator field was adjusted such that the regulator supplied 0.8 ampere to the alternator field and the separate direct current supply voltage provided the remainder (about 0.8 ampere) at no load. A 5-kva synchronous motor driving a direct current generator was selected as the alternator load. The load applied to the direct current generator was a lamp bank. The generator load was so adjusted that the alternator supplied 5.75-kva to the synchronous motor at unity power factor. By decreasing and increasing the field current of the synchronous motor the current was made to lag and lead the terminal voltage, respectively. The synchronous motor armature current was varied from 10.4 amperes (the value for 5.75-kva at unity power factor) to 10.8 amperes (the value for 7.5-kva at 0.5 power factor) for both the leading and lagging cases. The line voltages were measured with a Weston 300 volt voltmeter and the alternator rotor speed with a tachometer. The results are shown in the following table.

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Load	Power Factor	Line Voltages ab	ac	bc	Rotor Speed(RPM)
N.L.		208	208	208	1255
3.75-kva	1.0	208	208	208	1200
7.5 -kva	0.5 lag	208	208	208	1190
7.5 -kva	0.5 lead	208	208	208	1190

There was no motion of the voltmeter needle detected when changing power factors except when quickly shifting to the 0.5 lagging condition and then it was noted that the needle momentarily dropped about 0.5 volts and then returned to the value of regulated terminal voltage.

The wave forms of the line and phase voltages were observed on both a cathode ray oscilloscope and the General Electric Oscillograph for all the above conditions and there was no distortion noted. Oscillograms of the line voltage, ac, at no-load and 0.5 power factor lagging are shown in Figs. 13(a) and 13(b), respectively and the phase voltage, on, at 0.5 power factor lagging in Fig. 13(c). The presence of the 3rd harmonic in the terminal voltage is very evident in Fig. 13(a).

With the regulator operative and the alternator at no-load, the field current wave form was observed on the oscillograph and an oscillogram made. As shown in Fig. 13(d) the wave form is essentially direct current with a

[illegible] ON LINE

Load	Power Factor	Line Voltages ab	ac	bc	Motor Speed(RPM)
N.L.		208	208	208	1225
3.75-kva	1.0	208	208	208	1200
7.5 -kva	0.8 Lag	208	208	208	1190
7.5 -kva	0.8 Lead	208	208	208	1170

There was no motion of the voltmeter needle detected when changing power factors except when quickly shifting to the 0.8 lagging condition and then it was noted that the needle momentarily dropped about 0.5 volts and then returned to the value of regulated terminal voltage.

The wave forms of the line and phase voltages were observed on both a cathode ray oscilloscope and the General Electric Oscillograph for all the above conditions and there was no distortion noted. Oscillograms of the line voltage, ea, at no-load and 0.8 power factor lagging are shown in Figs. 13(a) and 13(b), respectively and the phase voltage, ea, at 0.8 power factor leading in Fig. 13(c). The presence of the [illegible] in the line and phase voltages is very evident in [illegible].

With the [illegible]

no-load, the [illegible]

oscillogram [illegible]

13(c) the wave [illegible]

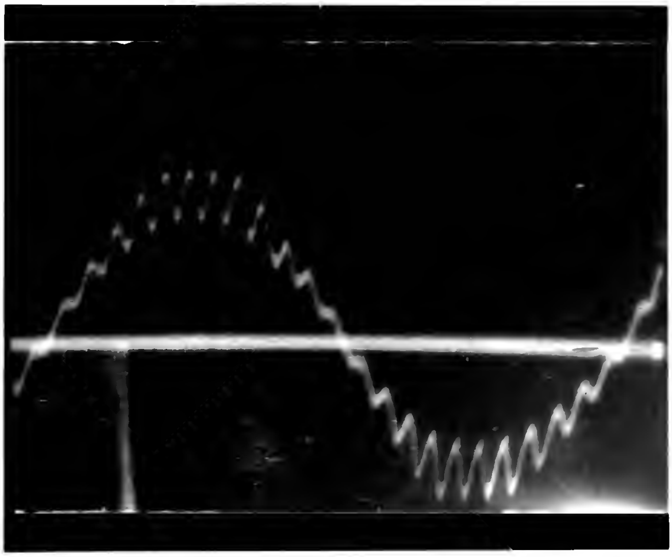

Fig.13(a) - Oscillogram of line voltage ac at no-load.

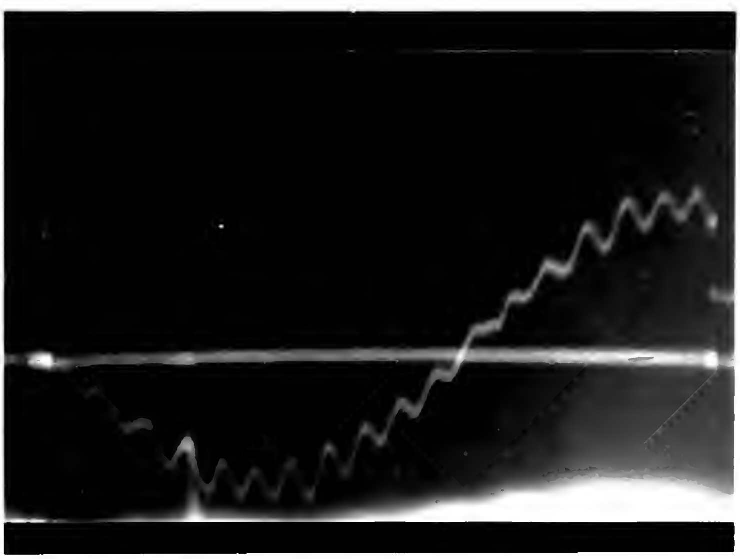

Fig. 13(b)- Oscillogram of line voltage ac at 7.5-kva,0.5 lagging power factor.

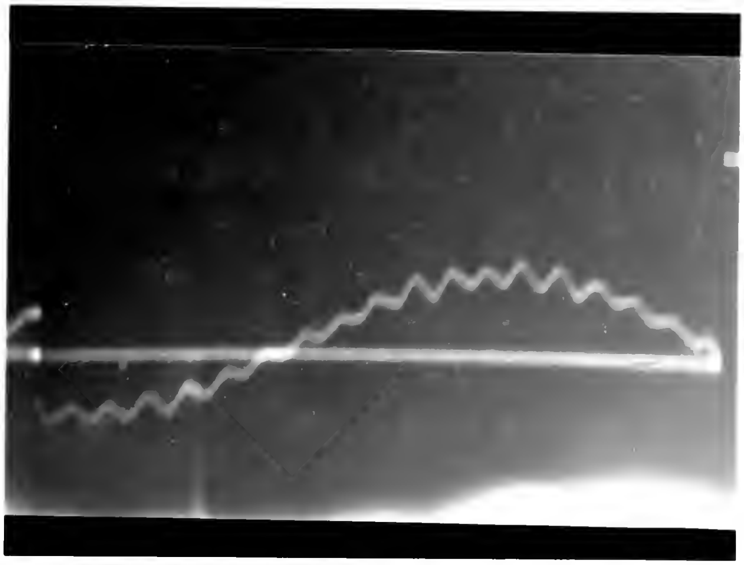

Fig.13(c)- Oscillogram of phase voltage oa at 7.5-kva, 0.5 lagging power factor.

Fig. 13(d)- Oscillogram of field current at no-load.

small 120-cycle ripple.

The above tests were conducted with an alternator phase supplying the thyratron heater voltage. They were repeated with the heaters drawing current from the commercial supply and there were no observed changes in the alternator regulation. For satisfactory operation the voltage applied to the lamp bridge is about 103.5 volts.

small 120-cycle ripple.

The above tests were conducted with an alternator phase supplying the thyratron heater voltage. They were repeated with the heaters drawing current from the commercial supply and there were no observed changes in the alternator regulation. For satisfactory operation the voltage applied to the lamp bridge is about 103.5 volts.

CONCLUSIONS

The regulator described in this paper provides very close voltage regulation over a wide range of power factors without any noticeable distortion in the terminal voltage wave form. It is noiseless in operation and contains no moving parts. The circuit is simple and requires a minimum of components, all of which are standard types commercially available at an economical price. There are no batteries required as is the case in many existing voltage regulators and the only parts that may need replacing are the four lamps in the voltage-sensitive circuit and the two thyratrons, but this should be necessary only after long periods of use. After initial excitation this regulator may be used as the alternator exciter, supplying all the field current. There is only one simple adjustment of the regulator required and that is the potentiometer, R_1, which controls the voltage applied to the lamp bridge. After this has once been adjusted to the proper terminal voltage of the alternator, no subsequent adjustment should be necessary.

All factors considered, this type of voltage regulator appears to be the solution for a simple, reliable, economical regulator for small alternators [illegible]

initial cost. It is estimated that this voltage regulator may be constructed for as little as $75.00

Unfortunately this regulator has its disadvantages and limitations. In its present form it is limited to a maximum current of 3.0 amperes. However, this can be easily increased by using a larger step-up transformer, T_2, but care must be taken to see that the current through a single thyratron does not exceed 2.5 amperes average. There are two disadvantages that may be eliminated by a small addition to the existing circuit arrangement. The heaters of the thyratrons must be heated for a period of 5 minutes prior to the application of anode voltage and the field current supplied by the separate direct current source must be decreased when the regulator is placed in operation. This may be done automatically by the use of a motor-driven time delay relay that closes five minutes after the heater voltage has been applied. When the relay closes, the thyratron circuit is closed and at the same time an additional resistance is inserted in series with the field rheostat that reduces the value of its current. A satisfactory motor-driven time delay relay may be purchased for about 15.00. This small additional expense is strongly recommended and will eliminate a possible personal error that

could damage the thyratrons, the cost of replacing one being more than the cost of the time delay relay. The circuit arrangement which includes this modification is shown in Fig. 14.

[illegible]

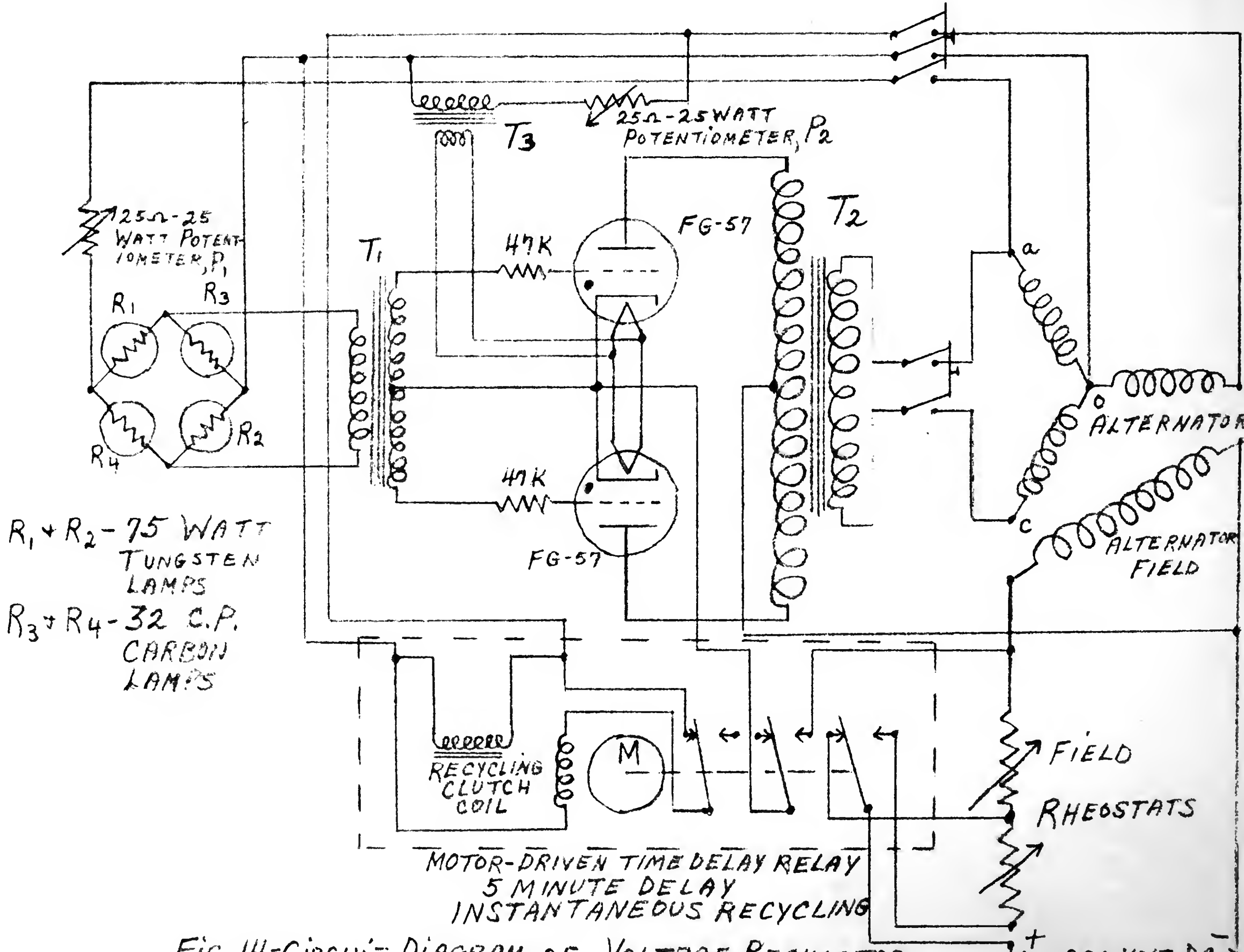

FIG. 14-CIRCUIT DIAGRAM OF VOLTAGE REGULATOR WITH MOTOR-DRIVEN TIME DELAY RELAY.

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(6) [illegible]

(7) [illegible]

(8) [illegible]

(9) [illegible]

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VITA

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